NASA TN D-148

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TECHNICAL NOTE

D-148

SINGLE-DEGREE-OF-FREEDOM SIMULATOR INVESTIGATION OF EFFECTS OF SUMMING DISPLAY-INSTRUMENT SIGNALS ON MAN-MACHINE CONTROL

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON December 1959

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SUMMARY

A limited study has been made, using analog computing equipment, of a man's ability to control "on instruments" an inertia with a proportional acceleration control. A single-degree-of-freedom system was simulated, and, at times, in order to increase the difficulty of the task, unrealistic disturbance inputs and system instability were used. The study was undertaken to evaluate performance obtained with the indicator responding to displacement and with anticipation provided by adding velocity and acceleration signals to the indicator.

The summing of displacement and velocity signals improved performance and had the effect of providing system damping. The addition of an acceleration signal was beneficial in some instances but was destabilizing in the absence of a velocity signal.

INTRODUCTION

There are many actual situations and an unlimited number of possible situations in which a man is called upon to control a system or vehicle "on instruments" or with visual information provided by an instrument display. When a man is observing an instrument display and actuating controls, which have the effect of modifying in some fashion the instrument indications, his ability to obtain or maintain desired indications is affected by many factors. One of these factors is the nature of the instrument display response to control actuation. When the man is piloting an aircraft, the elements determining the nature of this response can be grouped into three categories: the control system, the vehicle dynamics, and the instrumentation and display system. It is often possible to compensate for deficiencies occurring in one category by suitable modifications in another. For instance, in automatic stabilization systems the control system is provided with certain dynamic characteristics to compensate for deficiencies in the inherent vehicle dynamics. Compensation for deficient vehicle dynamic characteristics might also be effected by modifying the instrument display system.

The most desirable relation between control and indicator, as dependent upon the task, has been rather extensively studied in investigations of tracking problems such as references 1 and 2. In these studies the term "quickening" has been applied to system modifications which have the effect of providing the operator with immediate knowledge of the results of his own actions. Provision of the proper "quickening" terms in tracking tasks has been found to be very important.

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Instances of present concern of man's ability to control vehicles arise for vehicles operating with very low dynamic pressure. Flight conditions with low dynamic pressure can occur in hovering flight for vertical-take-off vehicles or at extreme altitude for some research vehicles. The vehicle may then be characterized as an inertia with an acceleration control provided by jet reaction with negligible aerodynamic contribution to stability, damping, or control.

A brief study has been made to determine whether a man with an instrument task of controlling and stabilizing a vehicle with poor static and dynamic stability would show improved ability with the addition of rate and acceleration gain to displacement indicators. A single-degree-of-freedom system representing a vehicle with inertia and a proportional acceleration control was simulated by using analog computing equipment.

SYMBOLS

A	instrument-signal gain ratio, $G_{\dot{\theta}}/G_{\theta}$, sec
B	instrument-signal gain ratio, $G_{\ddot{\theta}}/G_{\theta}$, sec^2
c	damping, ft-lb/radians/sec
G_c	control system gain, Q_c/δ_c, ft-lb/radians
G_{θ}	instrument displacement gain, N_{θ}/θ, in./radians
$G_{\dot{\theta}}$	instrument velocity gain, $N_{\dot{\theta}}/\dot{\theta}$, in./radians/sec
$G_{\ddot{\theta}}$	instrument acceleration gain, $N_{\ddot{\theta}}/\ddot{\theta}$, in./radians/sec^2
I	inertia, slug-ft^2

k	spring constant, ft-lb/radians
N	instrument needle displacement, in.
N_{θ}	vehicle displacement contribution to needle displacement, in.
$N_{\dot{\theta}}$	vehicle velocity contribution to needle displacement, in.
$N_{\ddot{\theta}}$	vehicle acceleration contribution to needle displacement, in.
Q	torque, ft-lb
Q_c	control torque, ft-lb
Q_d	disturbance torque, ft-lb
t	time, sec
θ	displacement, radians
$\lvert\theta\rvert_e$	average absolute θ error for 5-minute tasks of controlling a disturbance, radians
$\dot{\theta}$	velocity, radians/sec
$\ddot{\theta}$	acceleration, radians/sec^2
δ_c	controller deflection, radians
ζ	damping ratio

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GENERAL REMARKS

Many studies have been made of man's performance in control tasks, with various levels of difficulty, with performance related to man's transfer function. A guide to the type of modification of the characteristics of an instrument display for improving controllability can be obtained from the general design principle for a man-machine system postulated in reference 1. That is, design the man-machine system so that the transfer function required of the man is, mathematically, always as simple as possible and, wherever practicable, no more complex than that of a simple amplifier.

If a man is controlling a vehicle that can be represented by an inertia with an acceleration control and the instrument display is conventional in the sense that displacement on the instrument display represents displacement of the vehicle, rather specialized acquired learning or complex mental processes are required. If the task is that of making a change from one indicator position to another, the pilot must apply acceleration with the control to cause the indicator to acquire velocity and move toward the desired value and then apply reversed control in a proper sequence to obtain zero acceleration and velocity at the instant the indicator reaches the desired value. Thus
the pilot is required to perform in effect a second differentiation of L
the indicator position to assess the effect of his applied control. 6
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If the instrument display system was modified by the addition of 2
signals dependent upon vehicle velocity and acceleration to the existing displacement signals that drive the instruments, the pilot's task would be simplified and would more nearly approximate that of a simple amplifier.

With rate and acceleration gain superimposed on each displacement indicator and with positive acceleration, velocity, and displacement driving the indicator in the same direction, it might be expected that performance would improve because the pilot would be provided with anticipation. Both an extraneous reaction and an applied control reaction would cause an indicator movement when applied and before vehicle displacement had been affected. With the proper gain ratios the task of making a change of indicator position could be greatly simplified. At the start of the maneuver, application of control would soon drive the indicator to the desired value, mainly as a result of the acceleration and velocity signals to the indicator. If the indicator was then held at this value (holding this value should not be difficult inasmuch as an acceleration gain would provide an immediate indicator response to control application), the displacement would make a smooth damped approach to the desired value.

EQUIPMENT

The study was performed with the "pilot" or operator seated in a chair with a side-arm controller for right-hand operation and with the instrument display about 24 inches from the operator's eyes. A system with a single degree of freedom allowing rotation about an axis can be represented by

$$I\ddot{\theta} + c\dot{\theta} + k\theta = Q$$

where torque Q can be considered to be the sum of a torque Q_c resulting from control actuation by the operator and an externally impressed or disturbance torque Q_d. Analog computing equipment was used to solve the equation of the single-degree-of-freedom motion of the simulated vehicle. The study was primarily concerned with the condition where c and k are zero or inertia with no damping or restoring moment. At times negative values of c and k were used to increase the difficulty of the task.

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The side-arm controller, shown in figure 1, had freedom only about a fore-and-aft axis below the grip. The controller had an approximately linear spring restraint such that a moment of ±11.3 in-lb was required for full deflection ±0.67 radian. The control torque Q_c was proportional to controller deflection.

The instrument display (fig. 2) consisted of three edge-type panel milliammeters stacked one above another. Ordinarily two meters were masked and only one was visible. Having three meters available provided a convenient way of changing display information. The top meter displayed displacement, positive for a needle movement to the right, the center meter ordinarily displayed summed displacement and velocity, both positive to the right, and the bottom meter displayed summed displacement, velocity, and acceleration, positive to the right. Movement of the controller to the right would drive the needles to the right. The meters had a center zero and five divisions on each side of zero. The meter scale faces were 2.85 inches long by 0.9 inch wide formed as a portion of the surface of a vertical cylinder 4.6 inches in diameter. Although it is realized that the meter dynamic characteristics can be significant, in the discussion of method and results the needle is considered as responding exactly to the applied signal voltage. The amplitude response of a meter as the function of the frequency of a sinusoidal input is shown in figure 3. Phase information was not determined.

METHOD

Standard tasks were used to evaluate the effects of velocity and acceleration gain, most of the other system parameters being kept constant.

One type of task was that of applying control to try to keep the needle at zero when an external disturbance varying with time $Q_d(t)$ was present. The other type of task was that of making needle transitions, starting from an equilibrium condition with the needle at rest at the third division on one side of zero and applying control to cause it to move and come to rest at the third division on the other side of zero. No Q_d was present during the transition task.

Many elements of the system, such as inertia and gains, were considered as having certain specific values. It can be shown that certain combinations of the individual elements, or scaling parameters, determine the system response. The fundamental factor of the instrument presentation is considered to be (with the assumption of the perfect meter response) the instrument needle displacement (N inches) where

$$N = N_{\theta} + N_{\dot{\theta}} + N_{\ddot{\theta}}$$

or

$$N = G_{\theta}\theta + AG_{\theta}\dot{\theta} + BG_{\theta}\ddot{\theta}$$

When $c = 0$ and $k = 0$ and the system being controlled can be represented by

$$I\ddot{\theta} = Q$$

and when specific values of A and B are considered and a specific time history of operator control $\delta_c(t)$ is applied, the time history of N will be identical for identical values of $\frac{G_{\theta}G_c}{I}$ where G_c is the control gain or torque per unit controller deflection. In addition, when a disturbance $Q_d(t)$ is applied the needle time history is dependent upon $\frac{G_{\theta}Q_d}{I}$; thus the operator will have identical needle information and upon making identical control application will be in an identical situation if the ratio of G_c to some measure of the magnitude of Q_d is fixed and the time history of Q_d is fixed.

For the general case when the system being controlled is represented by

$$I\ddot{\theta} + c\dot{\theta} + k\theta = Q$$

identical situations exist if identical values of the scaling parameters c/I and k/I exist $\left(\text{in addition to identical values of the scaling parameters } \frac{G_{\theta}G_c}{I}, \; A, \; B, \text{ and } \frac{Q_d}{G_c}\right)$.

All tasks were performed with an I of 8 slug-feet^2, a G_{θ} of 6 inches per radian, and a G_c of 2.2 foot-pounds per radian. Two types of disturbance $Q_d(t)$ were used. One was a sine wave with a period of 16 seconds and a maximum amplitude of ±0.7 foot-pound or an average absolute value of 0.446 foot-pound. The other was a random disturbance with an average absolute value of 0.325 foot-pound. The random disturbance was generated by passing the output of a Gaussian noise generator (Electronic Associates, model 201) with a power-density spectrum flat to 32 cycles per second through a 6 decibel per octave filter with a corner frequency of 1/4 cycle per second. The absolute θ-deviation from zero could be integrated by the computing equipment. With the task of trying to keep the indicator needle at zero, with either disturbance, the average absolute θ error $|\theta|_e$ was obtained by integrating for a 5-minute period. The integration was started at the option of the operator when he felt confident that he was performing the task as well as possible.

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Recording equipment was used to obtain time-history traces representing Q_c, Q_d, θ, and N. All tasks were performed by the same operator.

RESULTS AND DISCUSSION

Early in the investigation it was found that the addition of acceleration and velocity signals had definite effects on the level of performance obtained in the tasks. The possible range of combinations of variables was very great, and only certain limited combinations and variations of parameters were tried.

There are three things that might be considered in evaluating the system performance during a task: (a) the opinion of the operator, (b) the integrated $|Q_c|$ being a measure of fuel consumed, and (c) task performance as shown by recorded values, such as time history of θ or average absolute error $|\theta|_e$. Generally speaking, the three criteria could be expected to show the same performance trends with system changes. In these tests equal attention was not given to the three criteria. A wide range of opinion was experienced, ranging from impossible to excellent, but opinion tends to be a rather elusive item to evaluate. Most of the evaluation was based on recorded data.

Evaluation With Specific Gain Ratios

In figures 4 to 6 are time-history records obtained of transitions, on the left, and control of the sine-wave disturbance. The top trace represents Q_c, the second trace represents Q_d, the third trace represents θ, and the bottom trace represents display-needle deflection, summed displacement and derivative signals. In figures 4(a), 5(a), and 6(a) the display-needle trace is not shown. In these instances the needle was driven by the displacement signal with no derivative information or A and B, the gain ratios of velocity to displacement and acceleration to displacement, were both zero. The needle trace would have been almost identical to the θ trace for the recording sensitivities that were used since the needle trace would have contained only θ information.

Values of $A = 0$ or 2.00 and values of $B = 0$ or 0.33 were used, with the exception of figure 4(d), during the tasks of figures 4 to 6. The best values of the gain ratios were found to be dependent to some extent upon the specific task being performed. Some effects of varying gain ratios are discussed later and, although not conclusively established as the best compromise values for a range of tasks, or the best values for any specific task, the use of a value of $A = 2.00$ and a value of $B = 0.33$ was found to yield generally acceptable results. L

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<u>$c = 0$, $k = 0$ (fig. 4)</u>.- The data of figure 4 were obtained with 1
$c = 0$ and $k = 0$. With $A = 0$, $B = 0$ (fig. 4(a)), the system per- 2
formance was not very satisfactory. Both transitions to and maintenance of desired values of θ (on the left side of the figure) were relatively difficult to achieve, as evident from the erratic nature of control input. Control input to suppress the sine-wave disturbance shows a degree of randomness, and the θ trace has some rather large deviations. The mean absolute θ error $|\theta|_e$ obtained for control of the sine-wave disturbance for a 5-minute period was 0.0274 radian.

With $A = 2.00$, $B = 0$ (fig. 4(b)), the system performance was very much better than that of figure 4(a), or adding a velocity signal to the displacement signal was beneficial. Transitions were easy to make. The first two were made with what the operator felt was the easiest and most comfortable procedure. Small amounts of control of rather long duration were used. The next two transitions show a few needle oscillations as the transitions were stopped. These were created by the type of transition that was made. The transitions were started with a control pulse, the needle was allowed to drift to the desired value, then the transition was terminated with control pulses or nudges. The last two transitions were made about as quickly as possible. For all transitions the θ trace has the appearance of a damped approach to the desired value. When the task was that of controlling the sine-wave disturbance the system performed well. Control input was relatively smooth and of proper magnitude and phase and resulted in very small θ deviations. The needle trace does not show any large or rapid movements that would be indicative of an unsatisfactory system as apparent to the operator. The value of $|\theta|_e$ (for control of the sine-wave disturbance) was 0.0059 radian. Integration of applied control $|Q_c|$ for the sine-wave control task, as a measure of fuel consumed, gave a 10 percent higher value with no derivative summing (fig. 4(a)) than for figure 4(b).

With $A = 2.00$, $B = 0.33$ (fig. 4(c)), the record traces are very similar in appearance to those of figure 4(b). Changing B from 0 to 0.33 or adding an acceleration signal did not have any pronounced effects in this instance. The value of $|\theta|_e$ was 0.0056 radian.

The record of figure 4(d) with $A = 3.00$, $B = 2.00$ is presented to show some of the effects that could result when the gain ratios used were not close to optimum values. When compared with figure 4(c), the most significant system change is the increase of B from 0.33 to 2.00. Applied control and the θ trace do not seem to be significantly different for either task of figures 4(d) and 4(c). However, the system of figure 4(d) is not as satisfactory to the operator and the reason can be seen in the trace of needle deflection. During the transitions there was a pronounced impression of needle bounce. The third and fourth transitions, which were initiated with a control pulse, have a very steep or rapid initial needle movement, followed by a backward movement and then a more gradual approach to the desired value. This pattern is a result of the high value of B or high acceleration gain. The needle trace during the sine-wave control task also depicts a different needle behavior as it shows many small but rapid movements. The value of $|\theta|_e$ was 0.0055 radian.

<u>$c = -6$, $k = 0$ (fig. 5)</u>.- The data of figure 5 were obtained for $c = -6$ and $k = 0$. A negative value of c (negative damping) was used to increase the difficulty of the task as compared with that of figure 4. The time to double amplitude $\frac{0.693}{-c/I}$ was 0.92 second.

With $A = 0$, $B = 0$ (fig. 5(a)), the transition task was very difficult. Continuous control operation was required to maintain approximately the desired θ. The sine-wave-control task was impossible to cope with; the control input was very poorly related to the disturbance input and θ exceeded full scale soon after the start of the sine wave and control was lost.

With $A = 2.00$, $B = 0$ (fig. 5(b)), it was possible to perform the tasks reasonably well. Transitions, however, required close undivided attention and could not be made in a variety of ways as in figure 4(b). Because of an oversight the needle trace was not obtained. The value of $|\theta|_e$ was 0.0120 radian.

With $A = 2.00$, $B = 0.33$ (fig. 5(c)), the performance of the transition task was very similar to that of figure 5(b). However, the smoother Q_c trace on the sine-wave-control task shows that adding the acceleration gain term improved performance on that task. The value of $|\theta|_e$ was 0.0062 radian.

<u>$c = 0$, $k = -8$ (fig. 6)</u>.- The data of figure 6 were obtained for $c = 0$ and $k = -8$. A negative value of k (negative spring constant) was used as another way of increasing the task difficulty as compared with that of figure 4. The time to double amplitude $\frac{0.693}{\sqrt{-k/I}}$ was

0.69 second, and a very large amount of reversed control was required to maintain the desired needle deflection from zero during the transition task.

With $A = 0$, $B = 0$ (fig. 6(a)), the transition task was very difficult. The sine-wave-control task was impossible to cope with; the control input was very poorly related to the disturbance input and θ exceeded full scale soon after the start of the sine wave and control was lost.

With $A = 2.00$, $B = 0$ (fig. 6(b)), the system performance was L
very much improved compared with that shown in figure 6(a). Transi- 6
tions required close undivided attention but were much smoother. Con- 1
trol of the sine wave was relatively good; $|\theta|_e$ was 0.0063 radian. 2

With $A = 2.00$, $B = 0.33$ (fig. 6(c)), the system performance improved, as shown by the somewhat smoother Q_c trace. Close and undivided attention was still required for the transition task. Control of the sine-wave disturbance was (for some unanalyzed reason) actually superior to that of figure 4(c); $|\theta|_e$ was 0.0040 radian. Although not shown on figure 6(c), the needle trace had smaller and more rapid movements than those of figure 4(c).

Evaluation With Task of Controlling

Random Disturbance

The random disturbance required a very active control response and was used to provide a difficult control task.

<u>Range of c, $k = 0$</u>.- Control of the random disturbance was evaluated with a range of values of c with $A = 0$, $B = 0$, $k = 0$ and with $A = 2.00$, $B = 0.33$, $k = 0$. Sample traces of Q_d, Q_c, and θ are shown in figure 7 for two time scales (figs. 7(a) and 7(b)) and for the two sets of gain ratios (figs. 7(b) and 7(c)). It can be seen that with derivative signals the θ error was smaller and the control input was much more closely related to the disturbance input.

Figure 8 shows the average absolute θ error $|\theta|_e$ as determined from 5-minute tasks of control of the random disturbance. Performance with derivative information ($A = 2.00$, $B = 0.33$) was much superior over the range of c that was used, and control could be maintained to greater negative values of c.

Various gain ratios with $c = 0$, $k = 0$.- The values obtained for $|\theta|_e$ during 5-minute control tasks for various gain ratios with $c = 0$ and $k = 0$ are presented in table I. Gain ratios $A = 2.00$, $B = 0.33$ were about as satisfactory as any in this group and definitely superior to zero gain ratios. There is another instance shown, $A = 0.50$, $B = 1.00$, where certain gain ratios can have undesirable effects; in this instance much higher value of $|\theta|_e$ than that with zero gain ratios resulted.

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General Comments on Effect of Gain Ratios

One way to examine the system properties would be to assume that the operator is capable of applying the control required, after an initial disturbance, to keep the needle on zero. Then the equation for needle deflection

$$N = G_\theta\theta + AG_\theta\dot{\theta} + BG_\theta\ddot{\theta}$$

would reduce to

$$B\ddot{\theta} + A\dot{\theta} + \theta = 0$$

which has the form of the equation of a free vibration with viscous damping.

It is apparent from the form of the equation that the term A is equivalent to a damping coefficient and the term B is equivalent to inertia. Critical damping of θ, or $\zeta = 1$, would be obtained if $\frac{A}{2\sqrt{B}} = 1$. In reality the operator could not keep the needle exactly on zero because his control input is the result of having seen a needle displacement and his lag time also prevents an immediate canceling of the displacement. A criterion in terms of critical damping should be considered as only a useful guide in examining the effects of system parameters on the performance of various tasks.

Another indication of the importance of gain ratio A to system damping was obtained during some trials with no Q_d and the seemingly simple task of keeping the needle on zero. With values of $A = 0$, $B = 0.33$, $k = 0$, and $c = 0$, the system performance was unsatisfactory. Even though at the start it was not difficult to keep the needle close to zero, a θ oscillation developed (probably originating and sustained by operator time lag) with a period of about 4 seconds and in about 6 cycles θ had built up to ± 0.07 radian, full control was being used, and the operator was very much aware of working hard but of not being master of the situation. Adding damping by changing c from 0 to 6 did not suppress the system oscillations.

The effect of gain ratios on the performance of a task which consisted of trying to keep the needle on zero with the disturbance being a series of Q_d pulses of 0.7 foot-pound of 3 seconds duration with 13 seconds between the start of each pulse is shown in figure 9. Here again it is seen that with $A = 2.00$, $B = 0.33$ and $\zeta = 1.74$ the performance was satisfactory and the θ trace was heavily damped. When the gain ratios were $A = 0.5$ and $B = 1.00$, and $\zeta = 0.25$, the θ trace shows light damping with a definite decrease of performance after the first pulse.

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Comparison of Summing and Separate Meters

Some tests were made to provide a comparison of the performance obtained with a single meter presenting summed information and with two adjacent meters, one presenting displacement information and the other presenting velocity or rate information. The tasks were transitions and control of the sine-wave disturbance. With the separate meter display, best results were obtained by giving primary attention to the rate meter. The order of performance obtained was: first, with summed displacement, velocity, and acceleration; second, with summed displacement and velocity; third, with separate displacement and velocity. The third was greatly superior to the performance with displacement only.

CONCLUDING REMARKS

Addition of velocity and acceleration information to the displacement signal driving an indicator has improved task performance for the specific conditions of this study. Summing velocity and displacement signals improved performance and had the effect of providing system damping. The addition of an acceleration signal was beneficial in some instances but was destabilizing in the absence of a velocity signal.

The limitations imposed upon the generality of the results by such factors as a single degree of freedom and the particular types of display instrument, controller, imposed disturbances, and tasks evaluated are not known. However, even with consideration of these limitations, it seems that performance gains would generally be obtained by adding derivative information to the display instrument when a man is required to control a vehicle with poor stability characteristics.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., August 13, 1959.

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2. Birmingham, H. P., Kahn, A., and Taylor, F. V.: A Demonstration of the Effects of Quickening in Multiple-Coordinate Control Tasks. Rep. 4380, Naval Res. Lab., June 23, 1954.

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TABLE I

AVERAGE ABSOLUTE θ ERROR FROM 5-MINUTE CONTROL TASKS

[Random disturbance; c = 0; k = 0]

Gain ratio A, sec	Gain ratio B, sec^2	Average absolute error, $\lvert\theta\rvert_e$, radians
0	0	0.0169
2.00	0	.0072
2.00	.25	.0083
2.00	.33	.0084, .0092
2.00	.50	.0086
2.00	1.00	.0105
2.00	2.00	.0143
1.00	1.00	.0132
.50	1.00	.0304

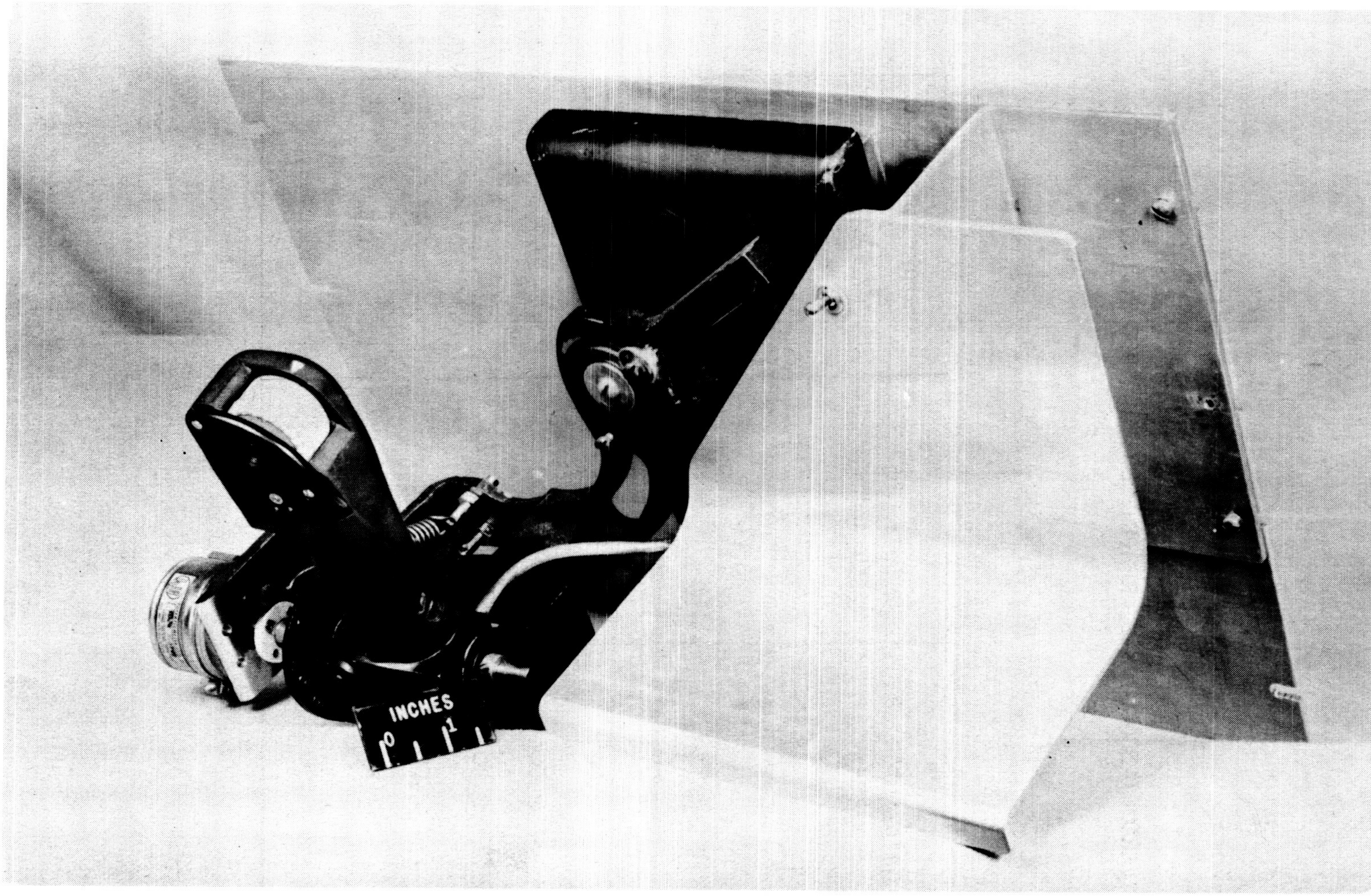

Figure 1.- Side-arm controller. L-59-1821

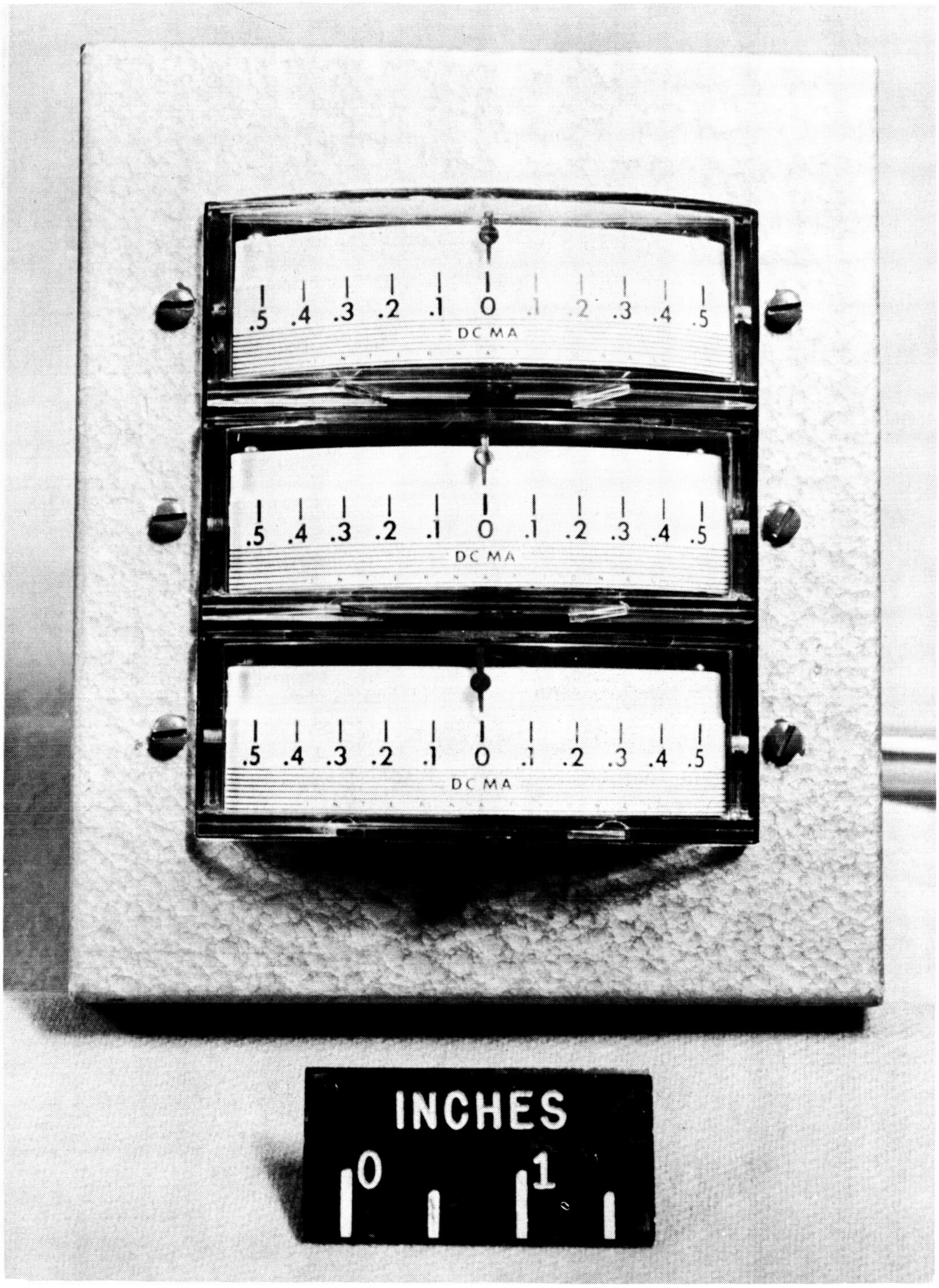

Figure 2.- Instrument display meters. L-59-1823

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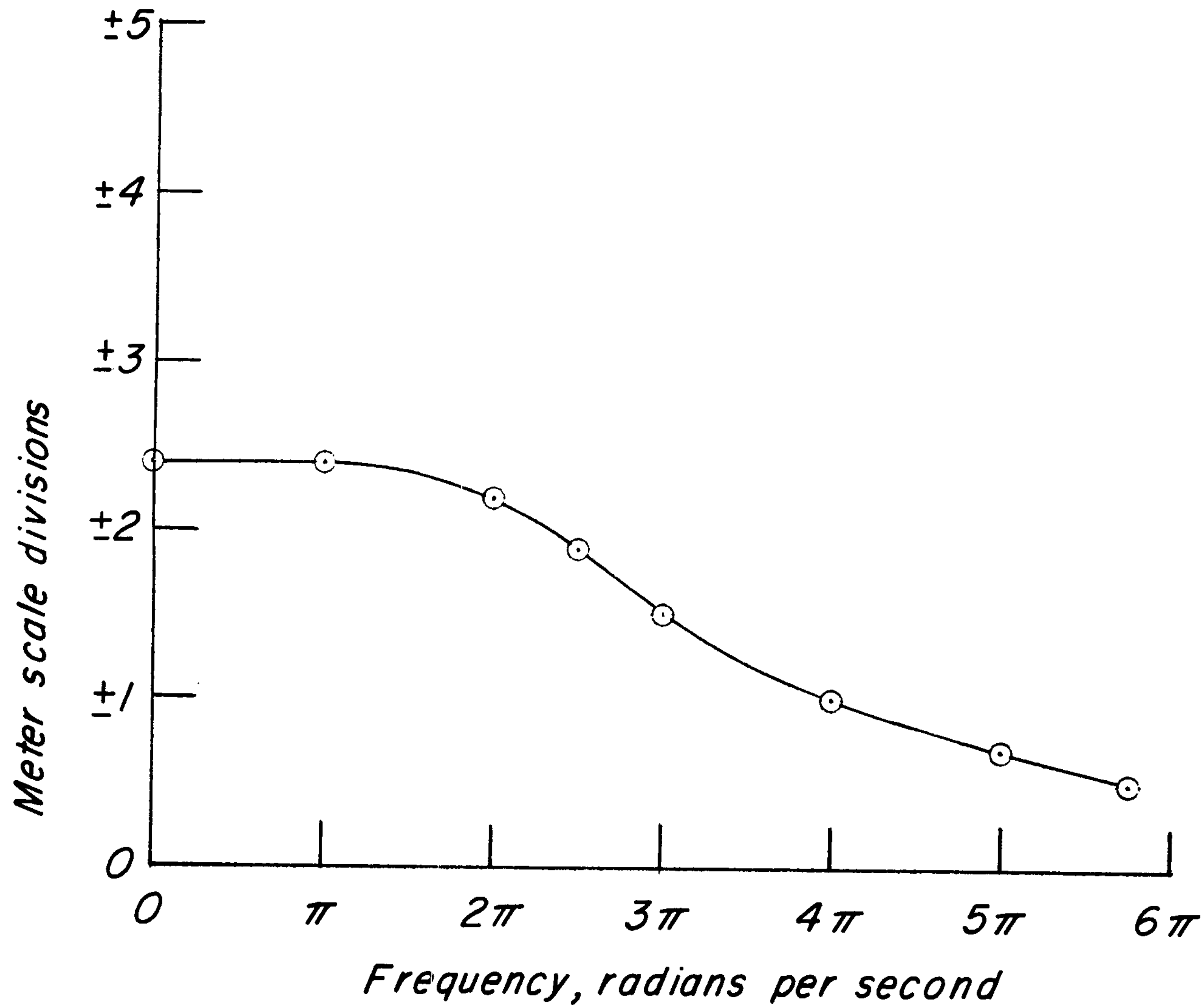
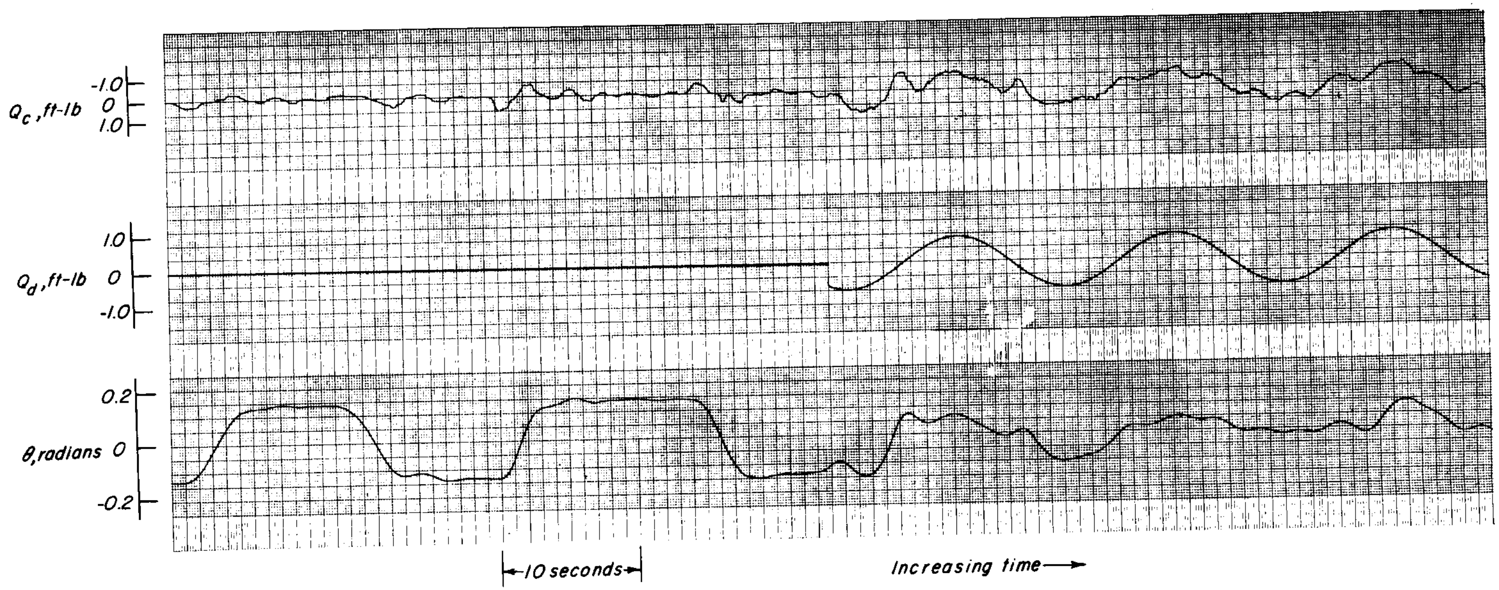
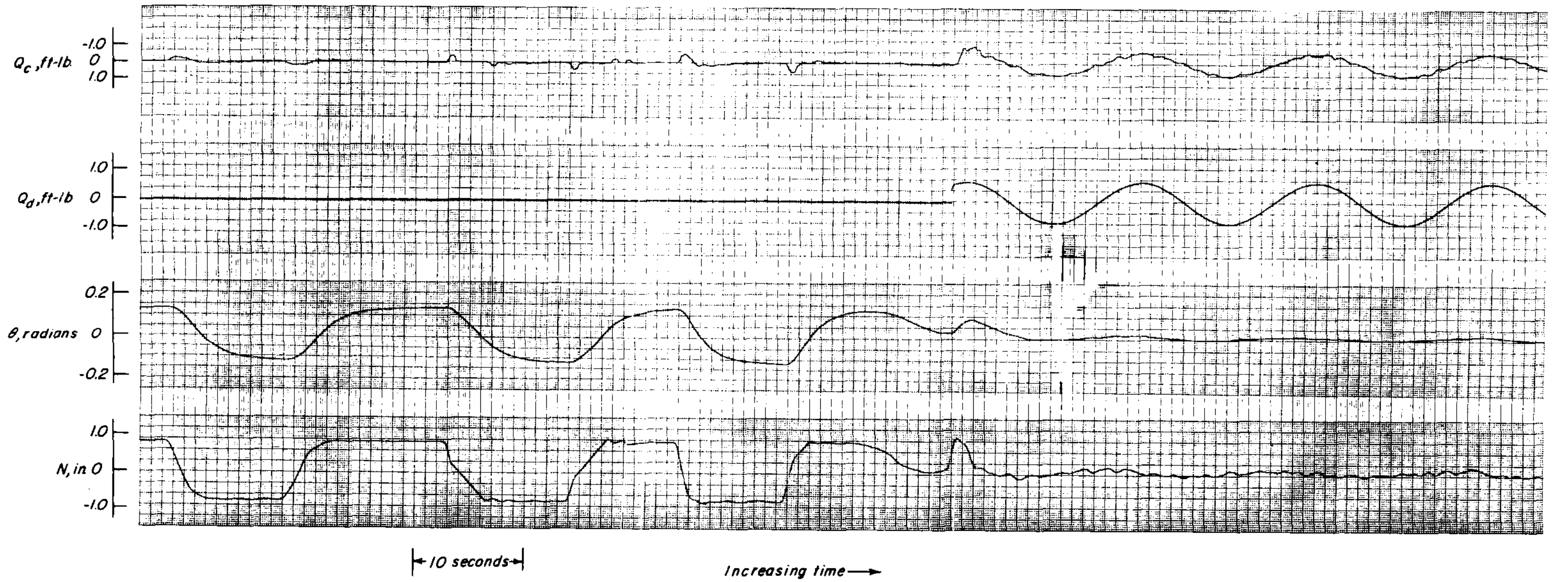


Figure 3.- Variation with frequency of the maximum amplitude of meter response to a sinusoidal input.



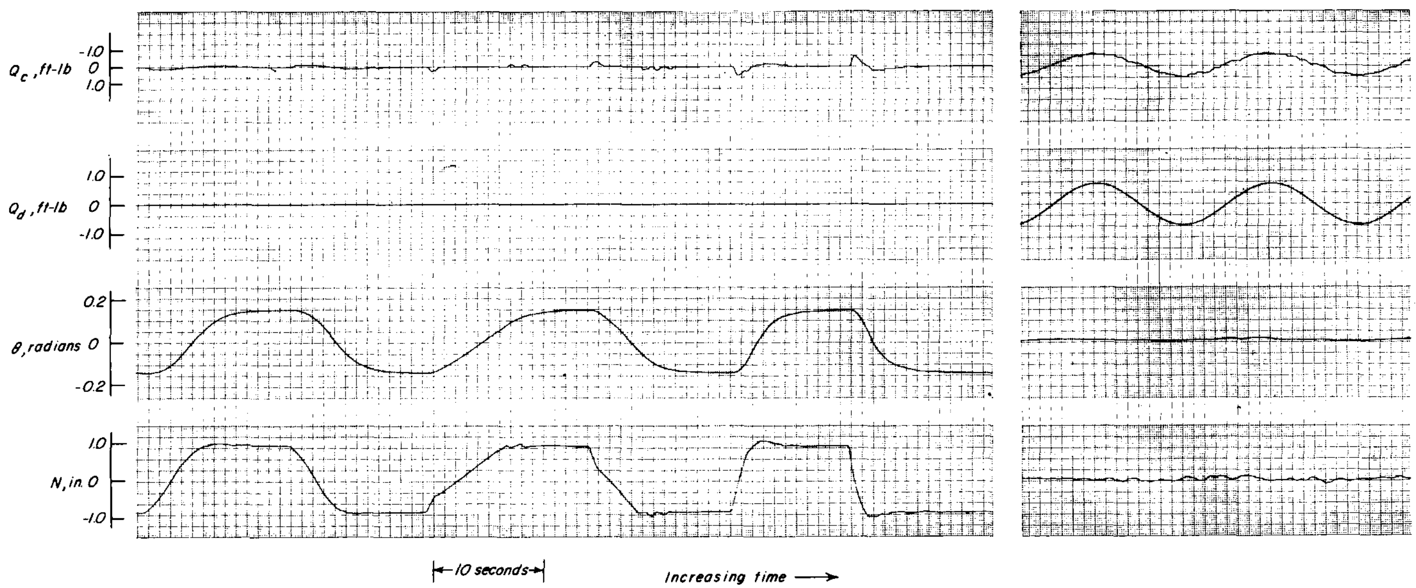
(a) $A = 0$; $B = 0$; $|\theta|_e = 0.0274$.

Figure 4.- Time-history traces of transitions, on the left, and of control of the sine-wave disturbance. $c = 0$; $k = 0$.



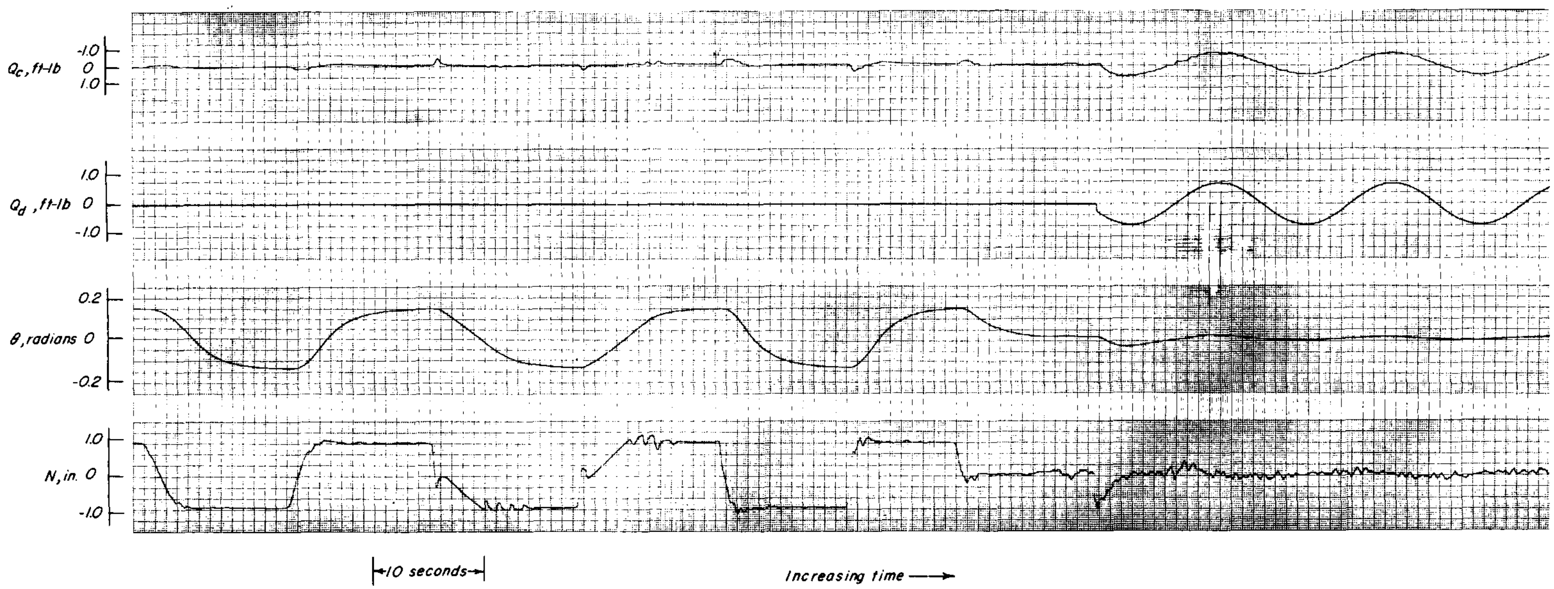
(b) $A = 2.00$; $B = 0$; $|\theta|_e = 0.0059$.

Figure 4.- Continued.



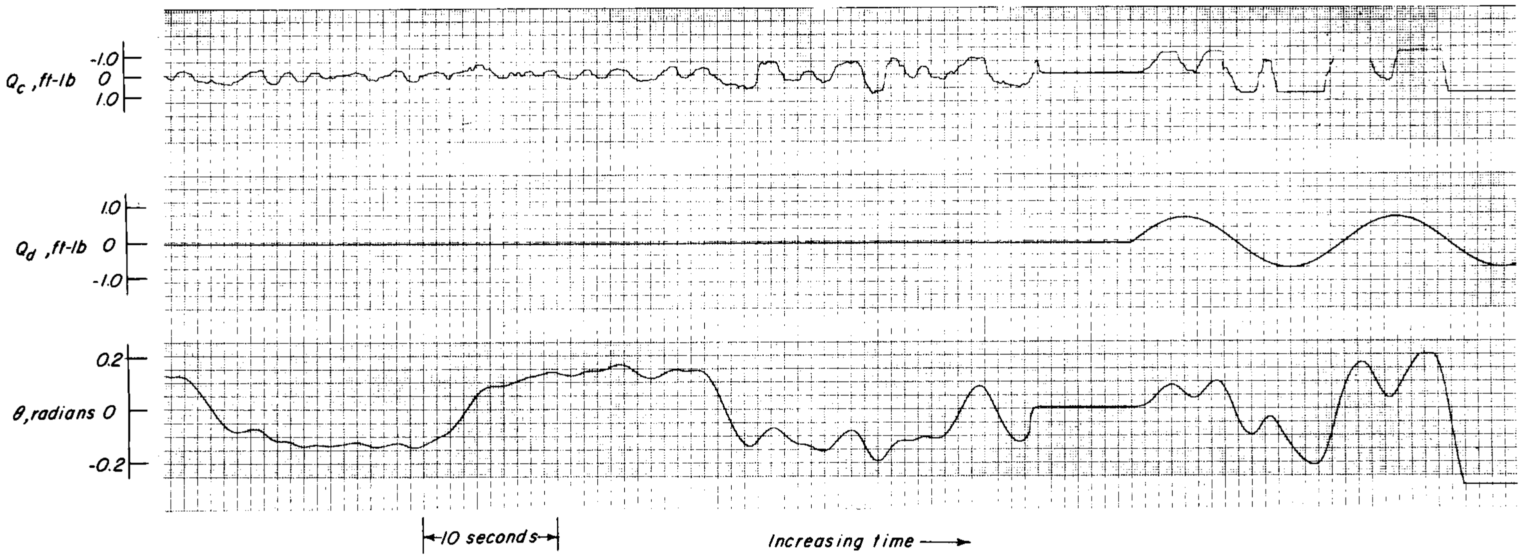
(c) $A = 2.00$; $B = 0.33$; $|\theta|_e = 0.0056$.

Figure 4.- Continued.



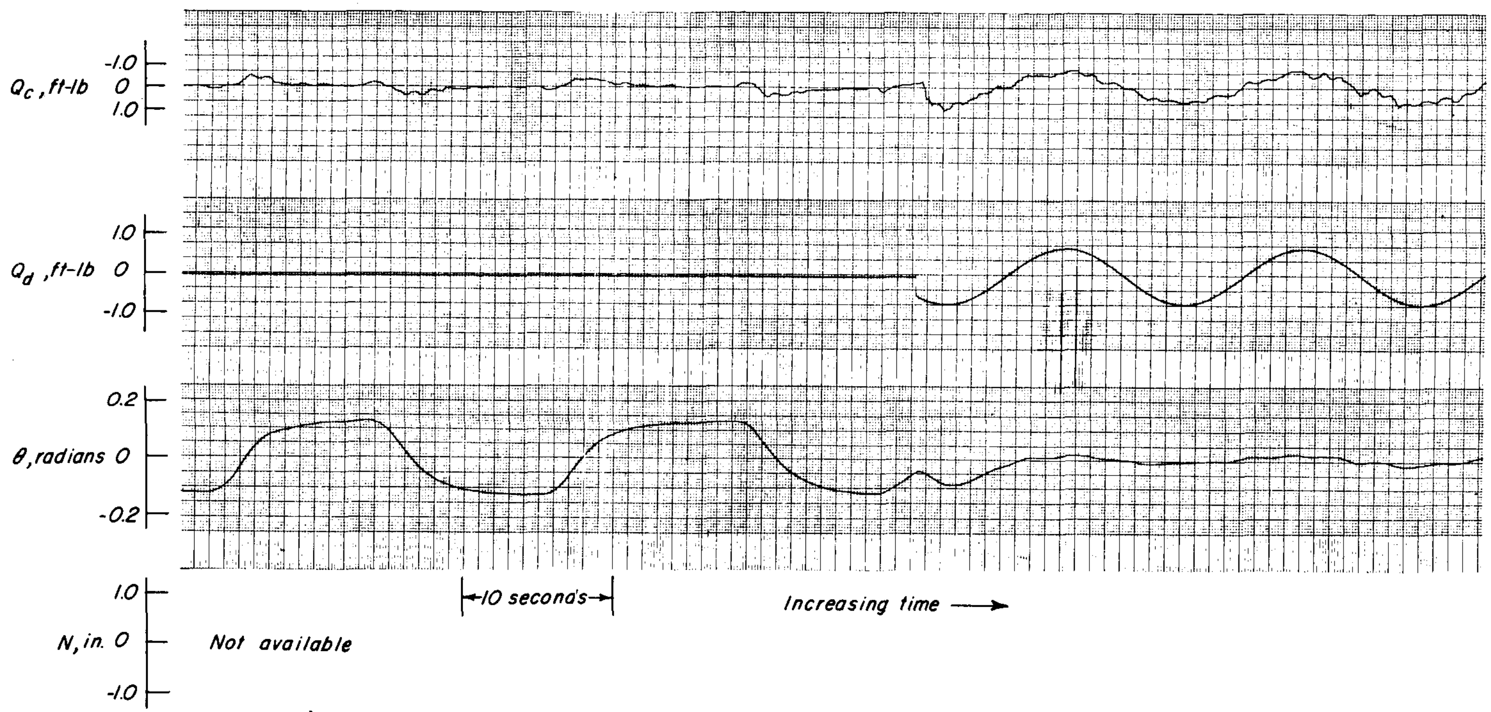
(d) A = 3.00; B = 2.00; $|\theta|_e = 0.0055$.

Figure 4.- Concluded.



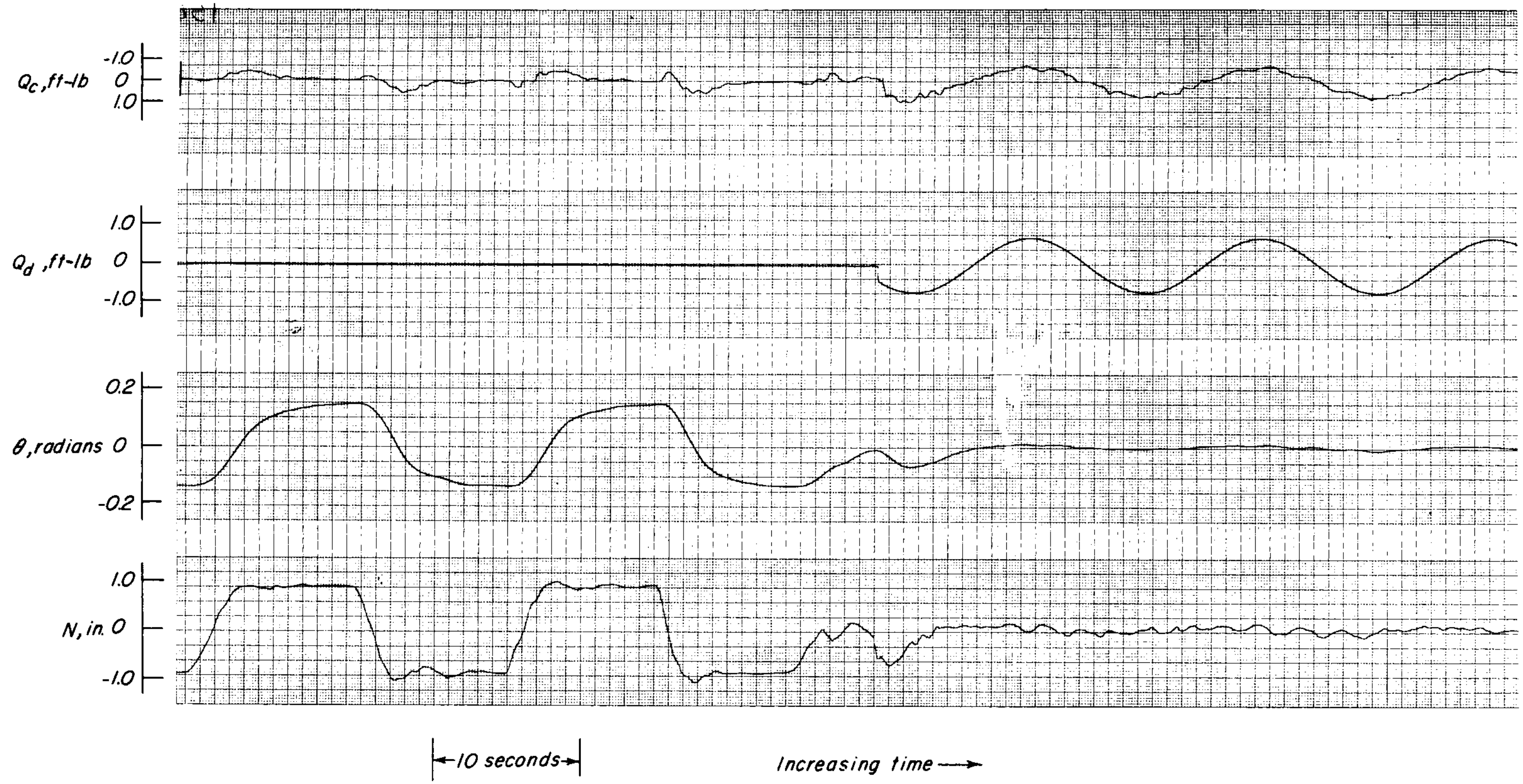
(a) $A = 0$; $B = 0$; $|\theta|_e$ lost.

Figure 5.- Time-history traces of transitions, on the left, and of control of the sine-wave disturbance. $c = -6$; $k = 0$.



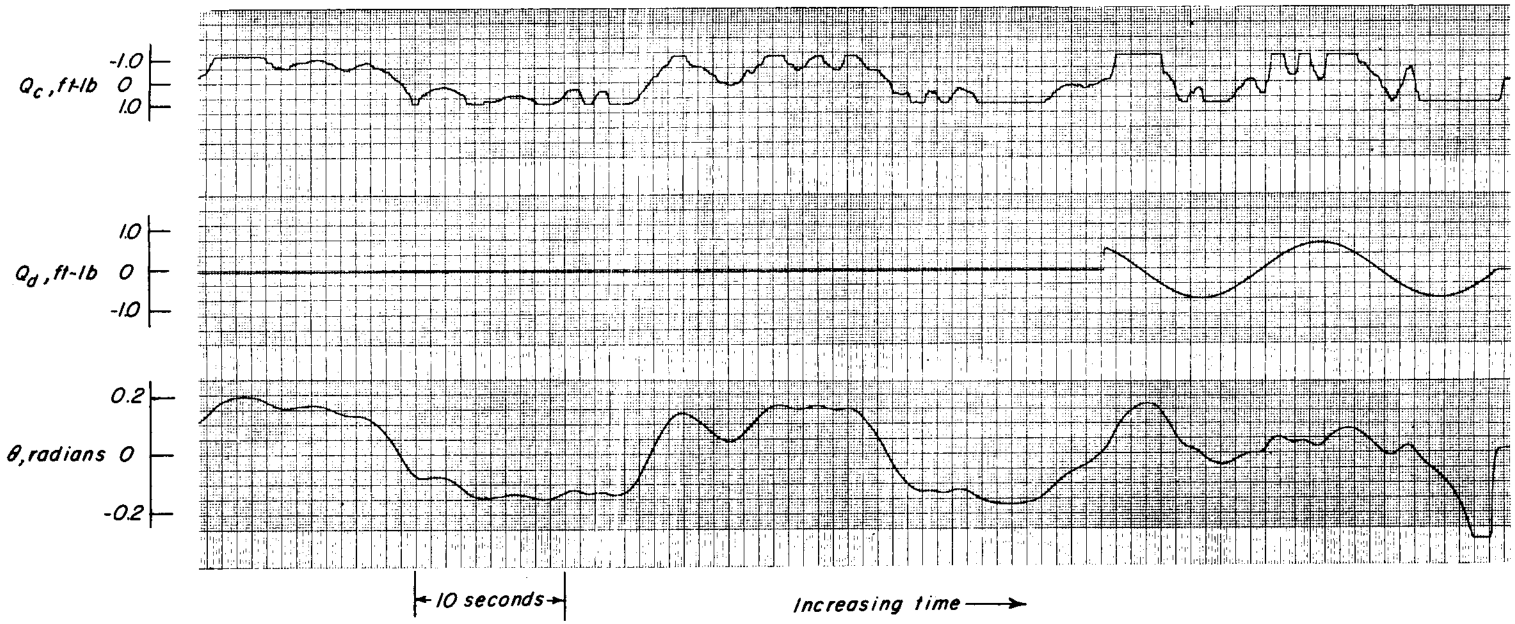
(b) $A = 2.00$; $B = 0$; $|\theta|_e = 0.0120$.

Figure 5.- Continued.



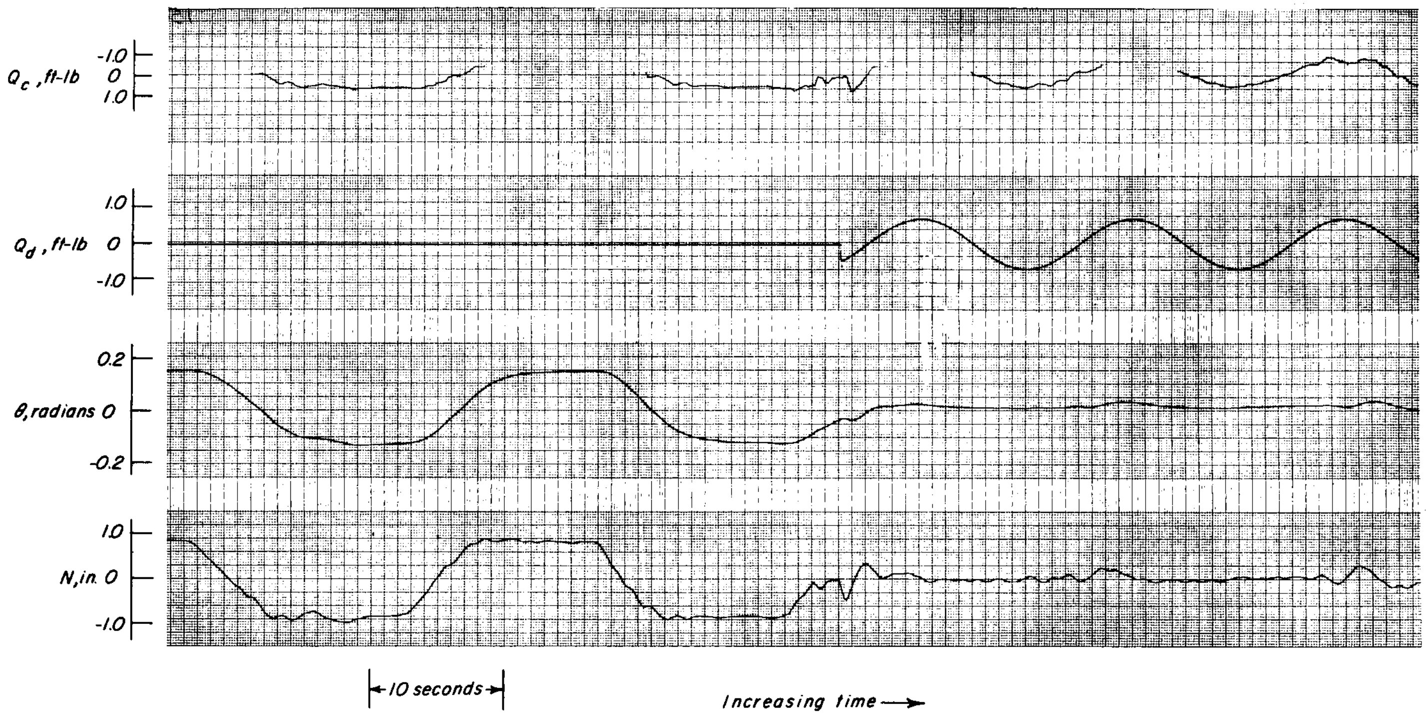
(c) A = 2.00; B = 0.33; $|\theta|_e = 0.0062$.

Figure 5.- Concluded.



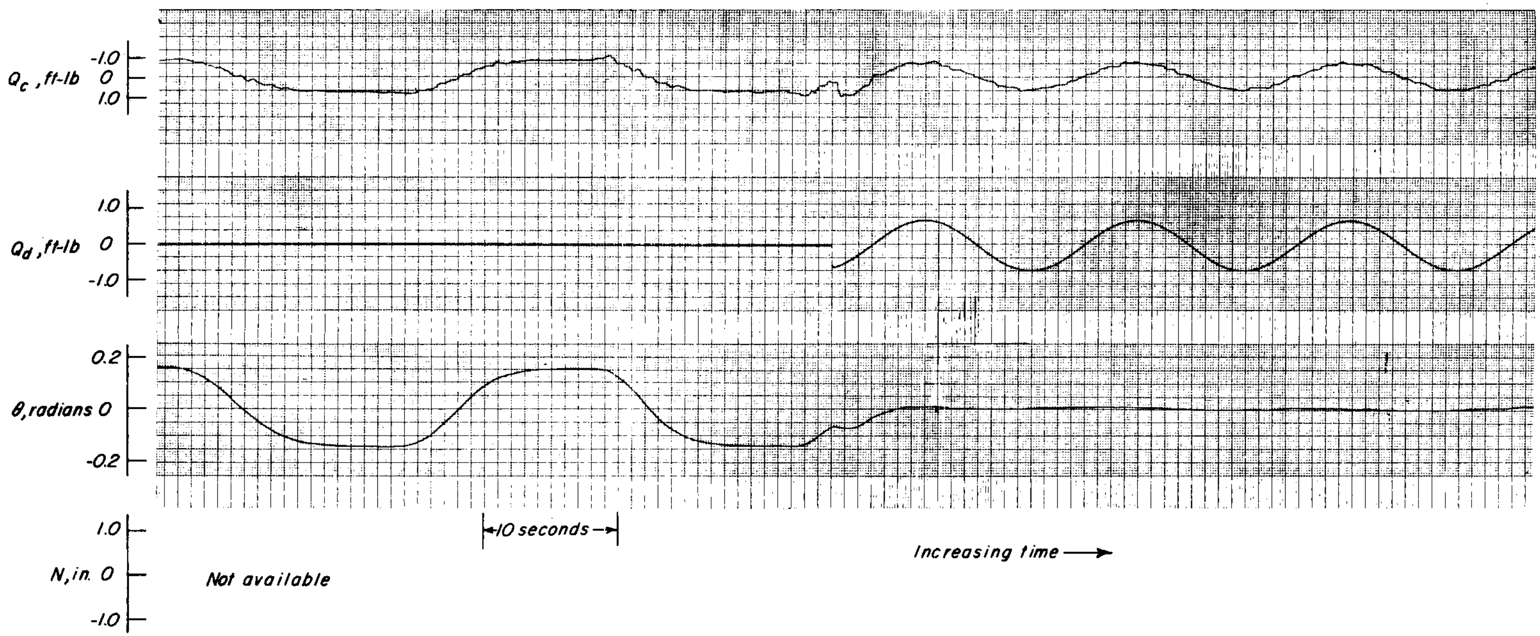
(a) $A = 0$; $B = 0$; $|\theta|_e$ lost.

Figure 6.- Time-history traces of transitions, on the left, and of control of the sine-wave disturbance. $c = 0$; $k = -8$.



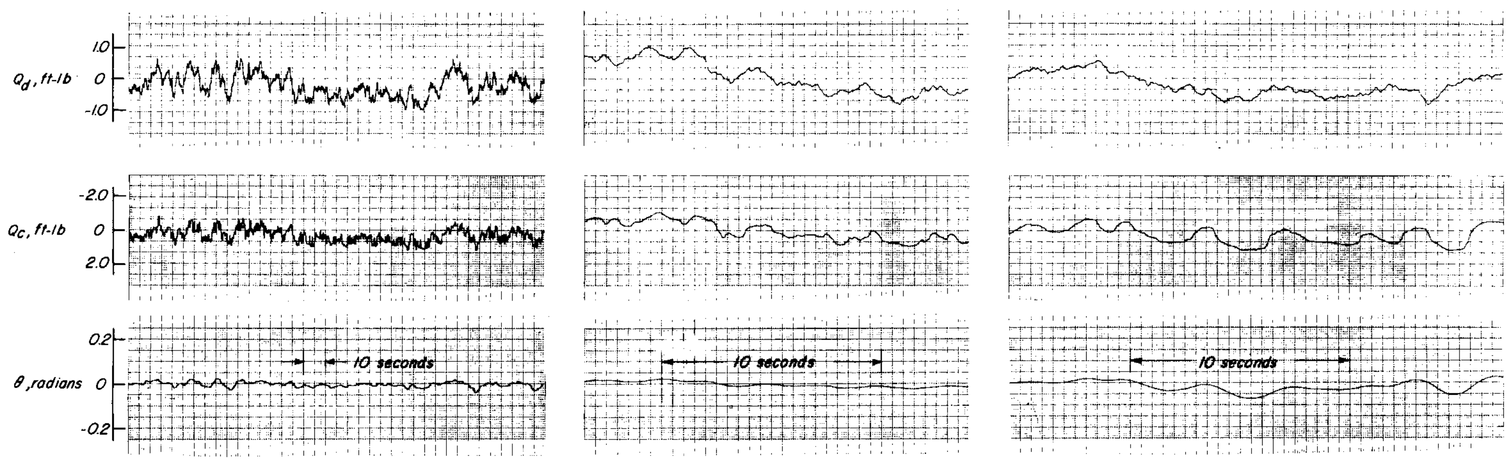
(b) $A = 2.00$; $B = 0$; $|\theta|_e = 0.0063$.

Figure 6.- Continued.



(c) $A = 2.00$; $B = 0.33$; $|\theta|_e = 0.0040$.

Figure 6.- Concluded.



(a) A = 2.00; B = 0.33. (b) A = 2.00; B = 0.33. (c) A = 0; B = 0.

Figure 7.- Sample traces obtained during control of random disturbance. c = 0; k = 0.

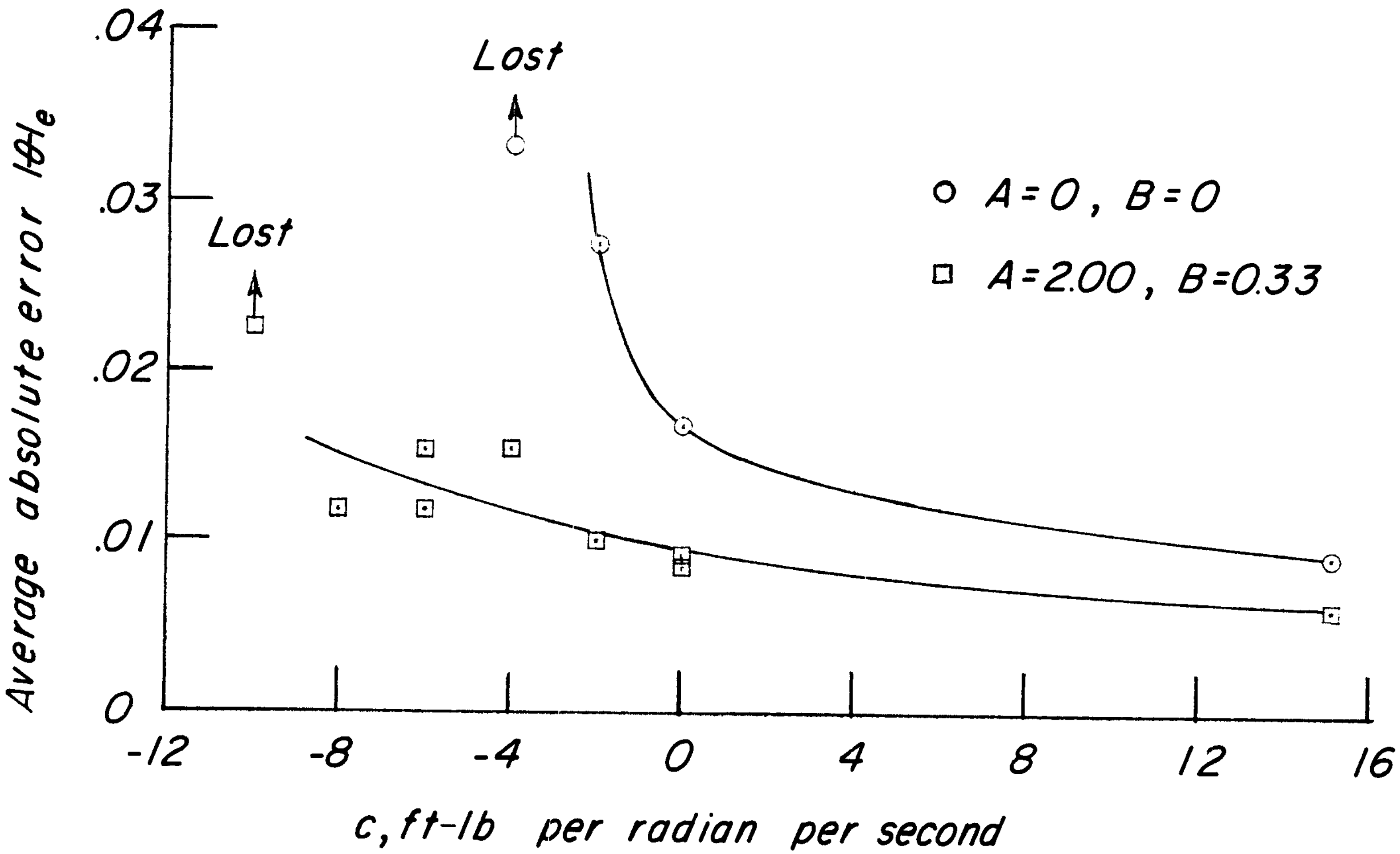


Figure 8.- Variation of θ error with c with and without derivative information added to the displacement indicator. $k = 0$; random disturbance.

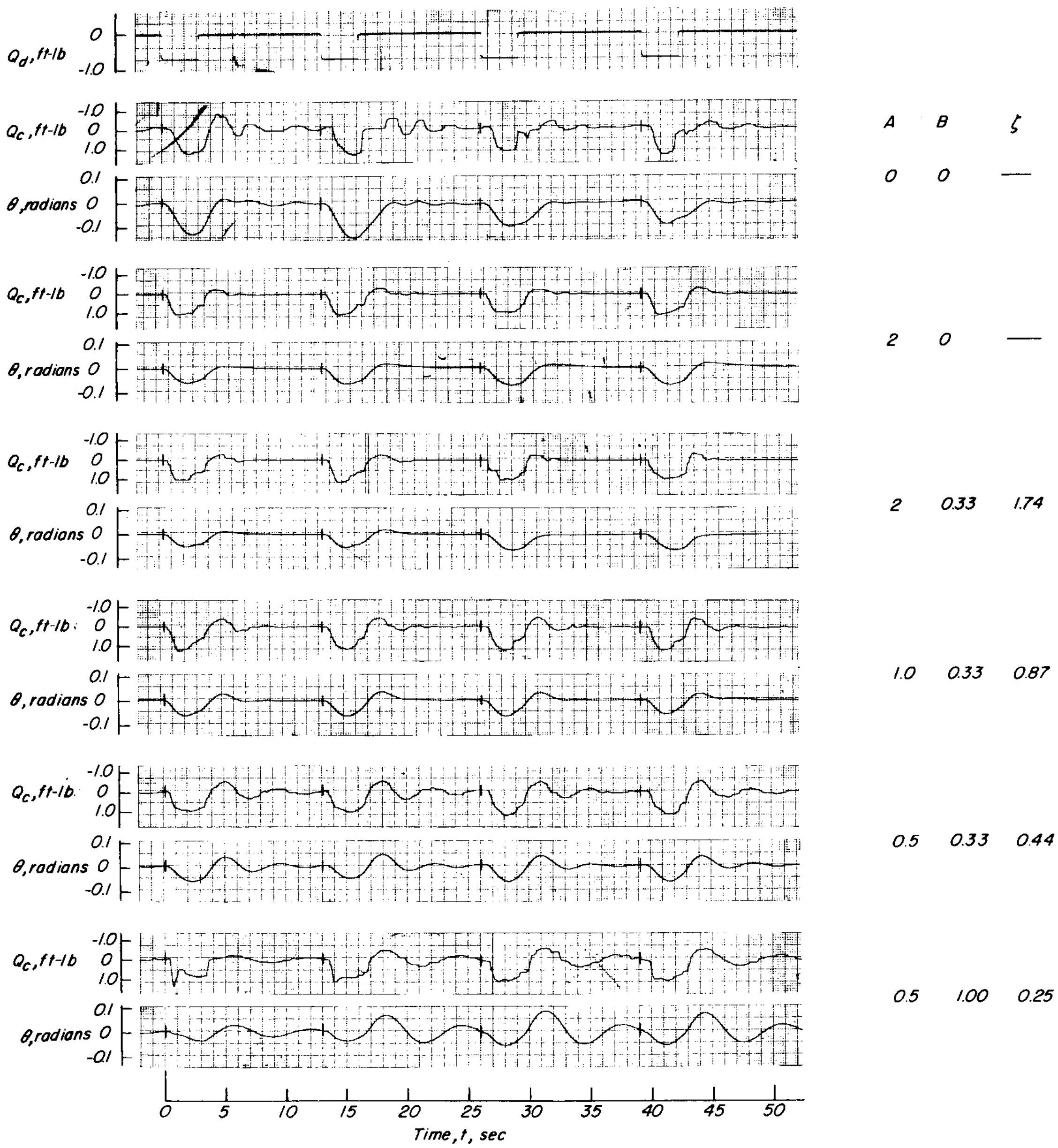


Figure 9.- Traces obtained during control of disturbance pulses with various gain ratios. c = 0; k = 0.